THE RESONANCE POTENTIALS OF HELIUM AND DOUBLE IMPACTS BY ELECTRONS IN HELIUM

By George Glockler*

Abstract

First and second critical potentials in helium.—A tube with five platinum electrodes was used to determine the first two critical potentials in carefully purified helium. The *inelastic impact method of Franck* was used over a pressure range from 0.13 to 13.00 mm and gave values of 19.87 ± 0.06 for the first, and 20.62 ± 0.06 volts for the second critical potential. The *method of Lenard* for pressures from 0.96 to 2.85 mm gave values of 19.83 ± 0.02 and 20.57 ± 0.06 volts. The spectroscopic value corresponding to the transition $1S \rightarrow 2s$ (A) is 19.77 volts and that corresponding to $1S \rightarrow 2S$ (B) is 20.55 volts. The observed difference between first and second critical potentials, 0.75 (Franck method), 0.74 volts (Lenard method), is in excellent agreement with the spectroscopic value of the difference $B-A$, 0.78 volts. The average *initial velocity correction* was determined by two different methods which led to concordant results.

Critical potentials in helium due to double impact.—Three critical potentials in helium near 40 volts were observed by the Franck method. The values are 39.62, 40.47 and 40.96 ± 0.04 volts, the last being the most prominent. The spectroscopic values for double impacts are 39.54 volts ($1S \rightarrow 2s$ and $1S \rightarrow 2s$), 40.32 volts ($1S \rightarrow 2s$ and $1S \rightarrow 2S$), and 40.89 volts ($1S \rightarrow 2s$ and $1S \rightarrow 2P$). The observed difference between the first critical potential and the most prominent double impact point is 21.09 volts, in excellent agreement with the spectroscopic value of the transition $1S \rightarrow 2P$, 21.12 volts.

SEVERAL experimental determinations of the critical potential of helium have been made by the method of electron impact.[1] Franck[2] has cleared up the situation regarding interpretation on the basis of Lyman's spectroscopic measurements[3] and at present it is accepted that the first critical potential of helium at 19.77 volts corresponds to a transition ($1S \rightarrow 2s$) from the normal to a metastable state.

In determining the critical potential of a gas by the method of electron impact a correction has to be made for the velocity distribution of the electrons, their initial velocity and for the contact potential difference between the filament and the other electrodes. In addition the efficiency of impact must be considered as shown by Sponer[4] and Dymond.[5] Franck

* National Research Fellow in Chemistry.

[1] K. T. Compton and F. L. Mohler, Bull. Nat. Res. Council, No. 48, p. 85 (1924).

[2] Franck, Zeits. f. Physik, **11**, 155 (1922).

[3] Lyman, Science, **56**, 167 (1922).

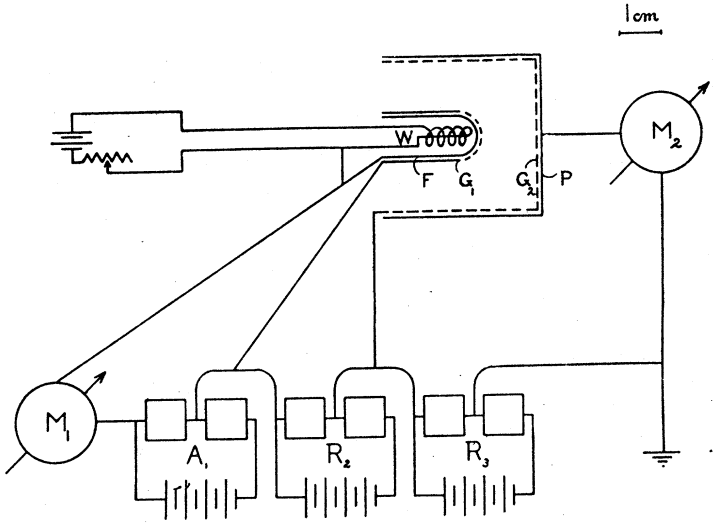
[4] Sponer, Zeits. f. Physik, **7**, 185 (1921).

[5] Dymond, Proc. Roy. Soc., **A107**, 291 (1925).

and Knipping[6] determined the last two corrections in the case of helium by measuring the volt-difference between the kinks in a current-potential curve corresponding to a single impact (type $A = 1S \rightarrow 2s$) and a double impact (type $A = 1S \rightarrow 2s$ and type $B = 1S \rightarrow 2S$). However, Dymond[5] has shown that in his experiments this difference is not 20.55 volts, but 20.9 volts, and he accordingly assumes that the double impact must be of the type BB. In this investigation the two single impacts appear as usual. The double impact that is most prominent occurs at 40.96 volts (corrected) and the difference between this point and the first drop is 21.09 volts corresponding in magnitude to the transition $1S \rightarrow 2P$. Indications were obtained at higher pressures which tend to show that the other types of double impact AA and AB also can occur.

Experimental Procedure

The five-electrode tube used is shown in Fig. 1. All electrodes are of platinum. The gauzes G_1 and G_2 are 52 mesh/inch and the wire is 0.004 inch thick. W is a tungsten filament that heated the calcium oxide



covered platinum thimble F by radiation. F is an equipotential surface. Between F and gauze G_1 an accelerating field is applied by means of the potentiometer A_1 of 10,000 ohms. M_1 is a galvanometer that measures the total emission from F. This total current was kept constant by regulating the external resistance in the heating circuit. M_2 is a galvanometer of 50,000 megohms sensitivity (880 ohms resistance) and is used

[6] Franck and Knipping, Zeits. f. Physik, **1**, 320 (1920).

at a scale distance of 3 meters. Both galvanometers were read on the same scale by means of two telescopes.

The helium was purified by sparking with a little added oxygen for 24 hours and then it was passed through a quartz tube containing magnesium ribbon, copper shavings, and granular copper oxide at 550°C, thus removing nitrogen, oxygen, and hydrogen. It was further purified by passing through a trap containing cocoanut charcoal immersed in liquid air and stored over phosphorus pentoxide. It was admitted into the experimental tube by means of a mercury trap so that no stopcocks were used at any place in the vacuum system. The pressures were read on a McLeod gauge. The voltages on the potentiometer were measured by means of a standard cell before and after each run. Readings were taken in steps of 20 ohms which corresponds to about 0.1 volt, since the battery supplying the potentiometer was 50 volts. Liquid air was kept on a trap to remove mercury vapor, except in the experiments using the Lenard method.

The Experimental Results

1. *The Franck method.* The current potential curves were obtained by two methods. The first of these was the inelastic impact method of Franck, in which the drop in electron current reaching the plate was determined as a function of the first accelerating field. No retarding

Table I

Franck method

Run	Press. mm Hg	Total drop across potentiometer before	after	Peaks of difference curves: First ohms	First volts	Second ohms	Second volts	Third ohms	Third volts	Filament volts	Filament amps.
0	0.13	34.06	34.06	.....	.....	....	.....			4.30	4.40
1	.81	34.06	34.06	6220	21.18	6410	21.82			5.00	5.40
2	.81	34.06	34.06	6226	21.20	6410	21.82			4.90	5.30
3	.83	34.06	34.06	6190	21.11	....	.....			4.80	5.25
4	.83	34.06	34.06	6202	21.12	6450	21.97			5.00	5.70
5	3.35	34.06	34.06	6218	21.18	....	.....			5.25	5.75
6	0.75	50.72	50.72	4130	20.93	4310	21.86			4.80	5.30
7	2.63	50.72	50.72	4170	21.15	....	.....	8320	42.19	5.50	6.50
8	5.50	50.84	50.84	4166	21.18	....	.....	8310	42.25	5.80	7.00
9	5.50	50.72	50.71	4158	21.10	....	.....	8330	42.25	5.80	7.20
10	5.50	50.72	50.72	4164	21.12	....	.....	8330	42.25	5.70	6.70
11	1.01	50.78	50.66	4166	21.13	4350	22.06	....	.....	4.80	6.10
12	1.83	50.64	50.63	4186	21.19	....	.....	8350	42.28	5.00	5.80
13	2.91	51.32	51.29	4183	21.23	....	.....	8240	42.27	5.25	6.25
14	3.70	51.17	51.13	4142	21.20	....	.....	8260	42.25	5.50	6.50
15	5.00	51.11	51.10	4122	21.06	....	.....	8260	42.20	5.60	6.75
16	13.00	50.97	50.96	4134	21.07	....	.....	8270	42.15	6.20	7.70
			Average values		21.14		21.89		42.23		
			Average deviation		± .06		± .07		± .04		

field was applied between the second grid and the plate. The experimental curves obtained by this method are shown in Fig. 2 (*B* and *D*) in which galvanometer readings are plotted against potentiometer resistance.

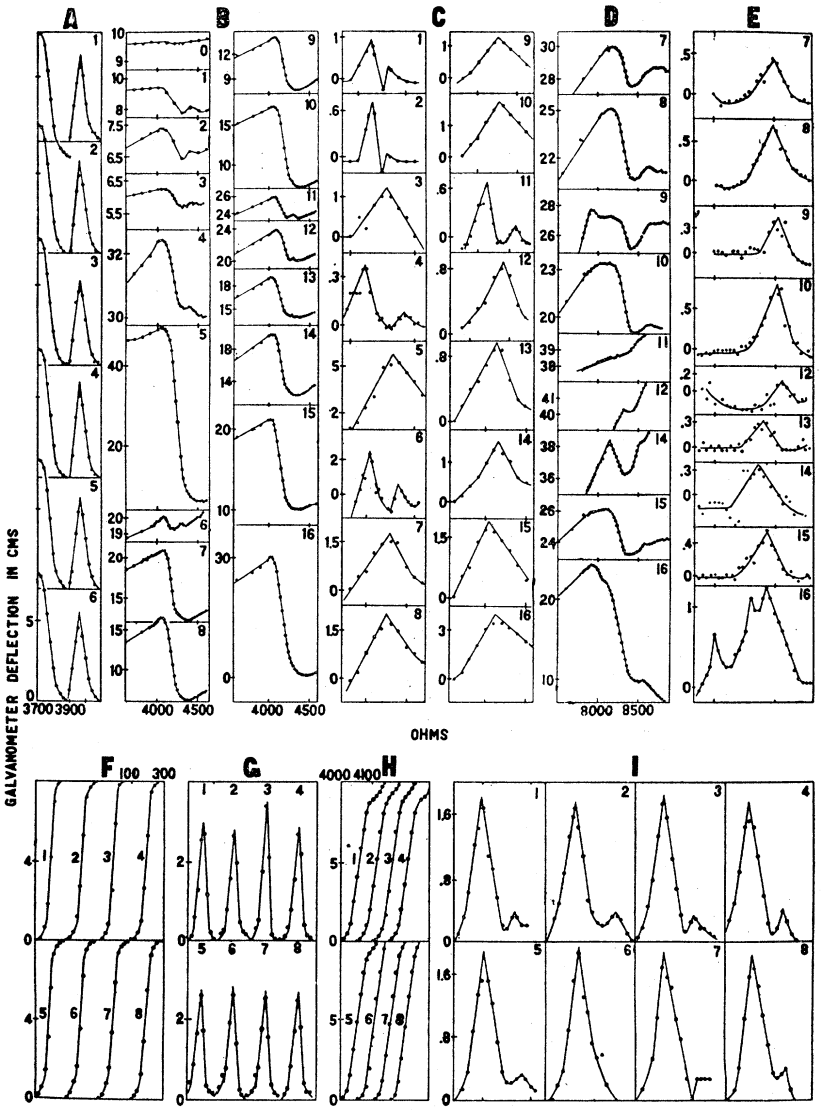


Fig. 2. Experimental current-potential curves.

These curves were then differentiated by taking the difference between successive galvanometer readings and replotting against potentiometer resistance. These difference-curves are shown in Fig. 2 (*C* and *E*). The

maxima of the difference-curves correspond to the points where *most* of the electrons from the filament have obtained enough energy to resonate. For the measurements in the neighborhood of 20 volts, the voltages corresponding to the maxima for the first current-drop are given in Table I, column 6, and for the second drop in Table I, column 8.

Measurements in the neighborhood of 40 volts were also made in the last eight experiments, and the peaks obtained are shown in Fig. 2 (*D* and *E*), and given in Table I, column 10.

The initial velocity correction (*Method I*). This correction was determined in a vacuum by applying a constant accelerating field (A_1) between F and G_1 of about 20 volts and by noting the decrease in plate-current as the retarding field (R_2) between G_1 and G_2 was increased. The correction is negative due to a contact potential between F and G_1.

If P_c is this contact potential and V_i is the actual velocity with which the electrons leave the filament, then a given electron can just reach the plate when

$$A_1+V_i+P_c=R_2 \tag{1}$$

where A_1 and R_2 are the accelerating and retarding fields respectively.

The results obtained are shown in Fig. 2 (*A*), where both the experimental curves and the difference curves are given, the latter being displaced to the right. In these curves galvanometer readings are plotted against the resistance, which gives the retarding field. It will be seen that the *first* drop in current due to R_2 occurs at 3700 ohms (=18.80 volts). This initial drop must be due to the slowest electrons. If they leave the filament with zero velocity, then

$$A_1+P_c=R_2 \tag{2}$$

and the contact potential is found to be acting as a retarding potential (i.e., $P_c=-1.6$ volts).

TABLE II

Data for determination of initial velocity correction (*pressure* 10^{-5}*mm*Hg)

Run	Total voltage first field A_1 before	after	Total voltage second field R_2 before	after	Field A_1 ohms	volts	Field R_2 at peak ohms	volts	Correction R_2-A_1	Filament amps	volts
1	50.66	50.66	50.41	50.41	4000	20.26	3770	19.00	−1.26	3.70	4.70
2	50.80	50.66	50.48	50.37	"	20.29	"	19.01	−1.28	3.70	4.75
3	51.39	51.35	51.19	51.17	"	20.56	"	19.30	−1.26	3.80	4.00
4	51.29	51.26	51.11	51.09	"	20.51	"	19.26	−1.25	3.70	3.80
5	51.18	51.19	50.99	51.01	"	20.47	3760	19.18	−1.29	3.75	3.85
6	50.98	50.97	50.80	50.79	"	20.38	"	19.10	−1.28	3.75	3.90
					Average correction				−1.27 volts		

The velocity distribution was thus determined with no gas in the tube. It might be thought that the distribution is different with helium present. However, the critical points should then show some trend with pressure. No such trend was observed. Of course the presence of the gas necessitates a greater heating current in the tungsten filament W as a good deal of heat is conducted away by the gas.

From the difference-curves the average correction was determined. The results are given in Table II.

2. *The Lenard method.* In the second method, Lenard curves were taken with a constant large retarding field (30 volts) between the second gauze G_2 and the plate. The results are shown in Fig. 2 (H and I) and they are summarized in Table III.

TABLE III

Lenard method

Run	Press. mm Hg	Total drop before	Total drop after	Peaks of diff.–curves First ohms	First volts	Second ohms	Second volts	Filament amp	Filament volts	Liq. air	Diff.–curve peaks for correction ohms	Diff.–curve peaks for correction volts
1	1.08	50.78	50.78	4102	20.82	4240	21.53	5.45	5.50	off	202	1.02
2	1.21	50.71	50.71	4112	20.85	4284	21.71	5.60	6.00	"	194	0.98
3	1.36	50.69	50.69	4114	20.85	4246	21.52	5.65	6.05	"	206	1.04
4	0.96	50.61	50.61	4108	20.79	4250	21.51	5.43	5.75	"	198	1.00
5	1.21	50.60	50.60	4118	20.84	4280	21.61	5.55	6.00	"	196	0.99
6	2.85	50.60	50.60	4118	20.84	....	.....	6.07	6.62	"	194	.98
7	1.14	50.50	50.50	4122	20.82	....	.....	5.60	6.10	on	194	.98
8	1.15	50.48	50.48	4124	20.82	4270	21.55	5.55	6.00	"	193	.98
		Average values			20.83		21.57					1.00
		Average deviation			± .02		± .06					± .02

The total rise in positive current was about 9 cm on the galvanometer scale in runs Nos. 1 to 5. In run 6 the total rise was 17 cm. However, the two last runs were made with liquid air on the charcoal so as to remove mercury vapor and the total rise was only 3 cm, showing that most of the current was probably due to positive ions of mercury produced by the metastable helium atoms.

The initial velocity correction (*Method II*). Before the Lenard experiments could be made the filament had to be recoated with calcium oxide as its emission had decreased. The correction for the recoated filament was determined by Method I as described above and Method II as described below. Both gave identical results.

In Method II, instead of making separate experiments in a vacuum with two fields, the correction was now determined with gas in the tube at the same pressure as was to be used in the Lenard experiment immediately following. The increase in electron current to the plate was

measured as the first accelerating field was increased from 0.5 volt to 1.5 volts while the other fields were zero. After such an experiment the retarding field (R_3) between G_2 and the plate was applied and a Lenard experiment was performed.

The correction for the recoated filament amounted to -1.00 volt, while previously it was -1.27 volts. The difference is presumably due to a change in contact-potential. It is important then to measure the correction for each filament and to make sure that it does not change.

The results are shown in Fig. 2 (F and G) and the last column of Table III. The figures given are the voltages A_1 which have to be applied in order to get the "average" electron to come through grid G_1 with approximately zero velocity and hence the correction has to be subtracted from the value of A_1 found in the later Lenard experiments. A few measurements of the correction were also made by Method I on the new filament and gave concordant results.

Summary of Results

When the proper corrections as described above are applied to the critical points, the values given in Table IV are obtained.

Table IV

Type	Transitions	Volts Spectroscopic	Franck method	Lenard method	Peak No.
A	$1S\rightarrow 2s$	19.77	19.87 ± 0.06	19.83 ± 0.02	1
B	$1S\rightarrow 2S$	20.55	$20.62\pm .06$	$20.57\pm .06$	2
AA	$1S\rightarrow 2s$ and $1S\rightarrow 2s$	39.54	39.62	....	3
AB	$1S\rightarrow 2s$ and $1S\rightarrow 2S$	40.32	40.47	....	4
AC	$1S\rightarrow 2s$ and $1S\rightarrow 2P$	40.89	$40.96\pm .04$	....	5
BB	$1S\rightarrow 2S$ and $1S\rightarrow 2S$	41.10	....	....	
BC	$1S\rightarrow 2S$ and $1S\rightarrow 2P$	41.67			

These values depend on the corrections applied. However, the differences between the peaks are independent of the initial velocity correction and the following quantities are obtained.

Table V

Transition	Spectroscopic	Franck method	Lenard method
$B-A$	0.78 volts	0.75 volts	0.74 volts
$AC-A$	21.12	21.09	....

Discussion of Results

It is seen that at a pressure of 0.13 mm (Fig. 2 B, Run O) no drop in current was obtained. At this pressure the mean free path of the electron (0.96 cm) is nearly as great as the distance between the gauzes (1.1 cm). At a pressure of 1 mm the m.f.p. of the electron is 1.25 mm, while the distance between the filament and grid G_1 is 0.5 mm. In some of the

experiments the pressure was so high that some of the electrons must have made impacts in the region between filament and grid G_1. However, the voltages at which the maximum occurs do not seem to be different.

In the Franck method a small retarding field of 0.34 volt between the plate P and grid G_2 was employed in runs 1 to 5, but no retarding field was used in the later experiments. Nevertheless the current dropped at the critical points, just the same as when the small retarding field was employed. This seems surprising, but the slow electrons produced may not diffuse to the plate as readily as do 20 volt electrons, or the drop in current may be the result of a small contact retarding voltage between the plate and grid G_2, or positive ions of an impurity produced by impacts of the second kind with excited helium atoms may diffuse to the plate. If the latter explanation should be the correct one, then both the current drop observed in the Franck method and the rise in current measured in the Lenard method are due to positive ions reaching the plate. At any rate, since the methods employed give results for helium in agreement with spectroscopy, they are thought to be practical and can be used to determine the critical potential of other substances for which no spectroscopic data exist.

Helium as a calibrating gas. These experiments show that the use of helium as a calibrating gas for resonance and ionization potential measurements as used by Hertz[7] is justified, since the corrected experimental value is 19.85 volts for the first resonance as compared with the spectroscopic value of 19.77 volts. This difference may be due to experimental error. Or it might be thought in accordance with the suggestion of Dymond that the maximum efficiency of resonance occurs at a voltage higher than the true critical potential, thus causing the peaks to come at higher voltage in these experiments than the spectroscopic values. However, Sponer[4] pointed out that it is possible, as in the present case, to apply *one* correction to a volt-scale and bring all critical points in agreement with spectroscopy. This means that either all critical points have a maximum of efficiency right near the critical point or that such a maximum is displaced the *same* volt amount for each critical potential. The first alternative seems the easier one to believe.

Furthermore, Hertz[7] has used helium as a calibrating gas to determine the resonance points for the other rare gases. In the case of neon he found the critical points in terms of helium using its spectroscopic values. Later he[8] actually obtained the neon resonance lines by Lyman's spectroscopic methods. The two methods checked. If the helium peaks were

[7] Hertz, Zeits. f. Physik **31**, 463 (1925).
[8] Hertz, Zeits. f. Physik **32**, 933 (1925).

displaced a certain amount due to the resonance-maximum appearing a few tenths of a volt higher than the true critical potentials, the calibration would have been incorrect and the two methods could not have checked. It seems, therefore, reasonable to assume that the efficiency of resonance is appreciable a few hundredths volt above the true critical potential.

The difference between the first and second critical point. Dymond[5] finds by a new differential method that the difference between the first and second critical potential in helium is 1.0 volt and not 0.8 volt, as is obtained from spectroscopy in the visible and also by Franck by his methods of electron impact. This new result is ascribed by Dymond to the fact that the maxima of resonance efficiency for the two types of impact occur at such electron energies so as to cause this larger difference. However, from Table V it is seen that the present experiments agree with the correct spectroscopic value of 0.78 volt.

The difference between single and double impacts. If the possible double transitions are arranged in order of energy required to produce them as in Table IV, it is seen that the difference between the most prominent peak at 40 volts and the first peak near 20 volts is equal to the transition $1S \rightarrow 2P$. The types AA and AB have only been obtained at the highest pressure used (Fig. 2 E, 16), whereas the value 40.96 volts (corrected) has been obtained consistently. Because this experimental value checks numerically with the type CA, it is ascribed to this transition. In order to understand why this transition should be more probable than the others, the relations between probability of impact and energy of impinging electron must be known. Dymond[5] has pointed out that the probability of double impact is the product of the probabilities of the single impacts at the voltage considered. At 40 volts the probability of type C impact may well be larger than of type A or B, and since at 20 volts the probability of type A is larger than of type B the present result would follow. Conversely it may be deduced from these experiments that near 40 volts the probability of impact for type C is greater than for A or B.

In conclusion I wish to thank Professor R. C. Tolman for his interest in this research.

GATES CHEMICAL LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY,
PASADENA, CALIFORNIA,
December 23, 1925.